***Report of the Symposium on***

# Fostering Spatial Competence: Behavioral, Symbolic and Brain Aspects

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***Organized by:***


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## Introduction and overview

This conference concerned the characterization of spatial competence and spatial learning in intelligent systems. Spatial competence is a fundamental aspect of intelligence, as identified at the behavioral, computational and biological levels. At the behavioral level, both experimental and psychometric evidence have led to the identification of distinct spatial representations and thought processes. At the computational level, recent work indicates that successful spatial reasoning by machine, like human spatial reasoning, often requires distinct metric representations in addition to the qualitative information sufficient for nonspatial problems. At the biological level, spatial functioning is known to involve distinct brain areas (i.e., the hippocampus, parietal cortex, and areas of prefrontal cortex). Spatial learning involves acquiring the ability to represent and reason about distance, shape, order, frames of reference, and other relations involving two and three dimensional extent, as well as the ability to use diagrams, models, and natural language to communicate such information.

Acquiring spatial competence is central to many disciplines and real-world skills. Fields such as geography and astronomy and tasks such as navigation and map use involve spatial relations of objects in the world. Fields such as mechanics and organic chemistry and tasks such as assembling and troubleshooting machinery involve understanding spatial relations of parts of objects and their dynamic interplay. In addition, spatial representations are involved in high-level mathematical understanding, and in understanding the diagrams and data visualizations commonly used in many disciplines. Thus, acquiring spatial competence is important to make a successful transition to work life in many work settings, but also essential to successful daily living even for individuals in relatively nonspatial occupations.

Spatial competence emerges gradually over long time periods in interaction with environmental input. In an era of rapid growth of technology, a trained workforce requires higher levels of spatial skill than ever before, and it is important to ascertain how to maximize potential in this area. While biological factors may affect spatial skill levels in individuals, there is also evidence that learning plays an important role in the expression of fully developed skills. There appears to be substantial range in the realization of individual abilities in the spatial domain, with these abilities far from being optimally achieved in the American population. Thus, the proper design of educational activities, curricula, and materials to stimulate spatial learning could create higher levels of spatial skill in the population.

There are many unsettled questions about the development of spatial competence, such as the degree of modularity of the system, the extent and nature of biological determination of normal development and individual differences, and the extent and nature of plasticity in the system or systems that underlie spatial competence. These questions were debated at the conference and are discussed in the more detailed sections later in this report. Nevertheless, the bottom-line message for the Transition from Childhood to the Workforce Initiative is that current understanding of spatial competence at the behavioral, biological, and computational levels of analysis is sufficiently advanced to justify optimism that research in the next few years can advance our understanding of spatial intelligence and spatial learning. Such research will provide a firmer basis for the development of education and training materials (including software) to maximize spatial learning through carefully designed and timed environmental input.

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Updating spatial position through nonvisual navigation and imagination

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Reaching in space: The co-evolvement of looking, acting, and remembering

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Eye movements during spoken language comprehension in natural tasks: Bridging the language-as-product and language-as-action traditions.

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## Agenda

**Session 1: Spatial Symbol Systems I**

**Judy DeLoache,** *University of Illinois*
Young children's use of symbolic representation to locate objects

**Ursula Bellugi,** *Salk Institute*
Spatial deficits and spatial enhancements

**Kenneth Forbus,** *Northwestern University*
Computational modeling of spatial representation and reasoning

**Lynn Liben,** *Pennsylvania State University*
Understanding spatial representations of the world: Organismic, experiential and educational dimensions

**David Uttal,** *Northwestern University*
Discussant

**Session 2: Spatial Symbol Systems II**

**Laura Carlson-Radvansky,** *Notre Dame University*
Grounding spatial language in perception

**Dedre Gentner,** *Northwestern University*
Spatial language and the development of spatial mapping

**Barbara Landau,** University of Delaware
(De)coupling of spatial language and spatial cognition: Evidence from Williams Syndrome

**Michael Tanenhaus,** *University of Rochester*
Eye movements during spoken language comprehension in natural tasks: Bridging the language-as-product and language-as-action traditions

**Terry Regier,** *University of Chicago*
Discussant

**Session 3: Spatial Coding**

**Janellen Huttenlocher,** *University of Chicago*
Locating objects: Geometric vs. Inductive organization in simple spaces

**Larry Hedges,** *University of Chicago*
Categorization of rational behavior

**John Rieser,** *Vanderbilt University*
Individual and blindness-related differences in dynamic spatial orientation while walking without vision: Two methods to sharpen the coupling of action and representation in persons who are blind

**Jeanne Sholl,** *Boston College*

Understanding competence in perspective taking

**Nora Newcombe,** *Temple University*
Discussant

**Session 4: Spatial Attention and Motor Control**

**A. Georgopoulos,** *University of Minnesota*
Motor cortical mechanisms of directional information processing

**Roberta Klatzky,** *Carnegie-Mellon University*
Updating spatial position through non-visual navigation and imagination

**Linda Smith,** *Indiana University*
Reaching in space: The co-evolvement of looking, acting and remembering

**Jim Hoffman,** *University of Delaware*
Discussant

**Session 5: Neural Bases of Spatial Competence**

**Nancy Kanwisher,** *MIT*
The parahippocampal place area and the perception of spatial layout

**Lynn Nadel,** *University of Arizona*
Cognitive mapping in computer-generated space

**Brad Postle,** *U. of Pennsylvania Medical School*
Neuropsychological and neuroimaging investigations of caudate nucleus contributions to spatial working memory: Implications for systems neuroscience and cognitive models

**Susan Levine,** *University of Chicago*
Discussant

## Session Summaries

### Spatial symbol systems

People use various external symbolic schemes to preserve spatial information, notably, graphic representations (such as maps, models, diagrams and graphs) and linguistic descriptions of space. Graphic and linguistic symbol systems are essential to adult life, both in work settings and in skills essential for daily living. Two sessions at the conference focused on these systems, roughly divided into a graphic and a linguistic section.

#### *Session 1: Maps, models, diagrams and graphs*

**Judy DeLoache** reviewed her program of research on young children's understanding of scale models. By age 3, most children succeed at finding an object hidden in a model in a room that the model represents, but only if the hiding locations are distinctive items, e.g. a pillow. When items are identical and children must use spatial relations, performance is much worse. There are other factors that also influence success at the model task. These data have implications for preschool education and the use of manipulatives.

**Ursula Bellugi** examined the spatial representation properties of sign language. To understand sign language, a person must keep track of the relations among movements of hands in a space. Dr. Bellugi's work reveals the importance of early sign language experience for other kinds of spatial competence. The fact of this influence suggests that education can have a profound impact on adult spatial ability.

**Ken Forbus** presented work on computational studies that have provided insights into the nature of spatial reasoning. For example, the essential role of metric representations in many spatial reasoning tasks (e.g. reasoning about shapes moving in contact) has been demonstrated by information-level arguments and simulations (Forbus, Nielsen & Faltings, 1991), providing an explanation for why people use diagrams in many tasks. The nature and role of qualitative representations in a variety of tasks, such as summarizing motion (Forbus, 1983) and reasoning about deflections of shapes under mechanical loads (Iwasaki, Tessler & Law, 1995) have been explored. Computational models of mental imagery (Kosslyn, 1996; Glasgow, 1992; Schwartz, 1996), the roles of diagrams in problem solving (Larkin & Simon, 1987), and learning spatial prepositions (Regier, 1996) provide additional examples of the importance of including metric information in spatial representations. Such insights are leading to useful software (cf. Joscowicz & Sacks, 1993) and have important implications for how people think about the graphical representation of spatial information.

**Lynn Liben** focused on the development of children's understanding of maps. Although young children understand some aspects of maps at an early age, they continue to struggle with some map concepts into elementary school. For example, they have difficulty using spatial location on maps to determine the actual location of objects in the world. Her work reveals both why these difficulties occur and possible educational solutions for helping young children to overcome them.

#### *Session 2: Spatial language*

**Laura Carlson-Radvansky** has investigated the grounding of spatial language in aspects of perception. Specifically, she suggested that spatial terms such as above in English are grounded in two perceptual processes: attention, and the vector sum coding of overall direction. This idea can be formalized in the attentional vector sum (AVS) model of spatial term acceptability. Seven experiments based on English spatial term usage support the AVS over competing models. Thus, the structure of linguistic spatial categories may be explicable in terms of independently-motivated perceptual processes. These processes may provide a constraint on cross-linguistic variation in the categorization of space.

**Dedre Gentner** and her colleagues have explored the possibility that language influences thought (a neo-Whorfian view) in the spatial domain. They have shown that learning words for higher-order visual patterns, such as symmetry or monotonic increase, can improve children s ability to detect these patterns in visual materials as shown on non-linguistic matching tasks (Gentner & Ratterman, 1991; Kotovsky & Gentner, 1996). Gentner suggested that, generally, spatial language and spatial thought are interdependent and mutual bootstrapping guides the development of the two systems. The manipulations used in the Gentner experiments show promise of being adaptable for education and training purposes.

**Barbara Landau** presented recent work in which she investigates the relation between spatial language and spatial cognition, by examining the abilities of individuals with Williams Syndrome (WS). These patients suffer severe impairments in spatial relational abilities but many aspects of their language faculty are spared--in fact, children with WS often seem linguistically precocious. She uses a range of tasks that elicit both linguistic and non-linguistic responses to the same stimuli. She finds that WS children's spatial representations use a clear reference system, but this system is fragile, breaking down for more distant locations. Similarly, the results for the linguistic task show a remarkable sparing of reference systems as children apply and understand terms, and yet this system is fragile, showing impairments relative to normally developing children. The pattern of performance overall reflected a similar but not identical structural representation of space, suggesting some degree of independence in the development of spatial language.

**Michael Tanenhaus** has cast doubt on the position that the ability to process syntax is an autonomous module of the mind. He has investigated language comprehension in tasks involving naturalistic communication in a shared spatial environment. For example, one person might say to another, "Pick up the apple on the dish and place it next to the knife." Eye movements recorded during comprehension of these sentences suggest that sentence processing is influenced by the spatial context. Significantly, this influence is seen in mid-sentence, signaling a penetration of spatial context into the core of syntactic processing.

### Spatial coding

**Janellen Huttenlocher** summarized evidence suggesting that representation of spatial information is multilevel, including both fine-grained and categorical coding. That is, location is coded in terms of frames of reference (spatial categories) and also, within a reference frame, particular locations are coded in terms of direction and distance from landmarks such as edges and distinctive objects. Hierarchical organization of these levels is a salient feature of spatial representations, which gives rise to biases in spatial judgment associated with categorization. According to the Huttenlocher and Hedges model, people performing spatial estimation combine inexactly represented fine-grain locations with categories. This process produces a characteristic pattern of bias across a category towards the category center. (Thus, bias patterns can reveal what categories people are using.) Even though the process produces bias in individual estimates, it may increase average accuracy by decreasing the variability of estimates, as in Bayesian statistics. (It should be noted that people generally are not aware of using categories in estimation; they believe they simply encode and reproduce particular locations.) Huttenlocher

presented a new series of studies showing that categorical organization is surprisingly difficult to alter. Even when people view displays that seem to clearly invite them to consider the circle as diagonally bisected rather than organized by horizontal and vertical bisectors, they do not in fact adopt such categorization.

**Larry Hedges** followed up on this presentation by discussing another new direction the Huttenlocher-Hedges work has taken. He argued that adjustment toward the category prototype is an adaptive process even when distributions are not in fact such that placement at the prototype is more likely than placement elsewhere. Together, the Huttenlocher-Hedges presentation raised questions about the plasticity of the hierarchical coding system, suggesting instead the possibility of a more hard-wired biological system.

Aspects of **John Rieser**'s research program lead one to believe that development is driven at least in part by inductive processes and by learning with feedback. The findings are these. First, adults exposed to anomalous patterns of correlation between what they are doing motorically and what they are experiencing visually adjust their judgments so that the new correlation (based on a few minutes of experience) affects the true correlation. Second, early-blind individuals and, even more interestingly, individuals early afflicted with a restricted range of sight, have problems with dynamic spatial orientation; that is, using information about direction and distance of motion to reorient within an array of learned locations. However, juxtaposing these findings does pose an issue. The first findings show that a lifetime of experience can be overridden, to some extent, by a relatively brief manipulation. What is implied is an astounding flexibility or malleability, well beyond any kind of sensitive period. Yet the second set of findings implies the existence of a sensitive period of some sort. The individual with late-onset visual impairments does not recalibrate to the extent one might expect given the first set of findings. This contrast may imply that degraded input has effects primarily during an early sensitive period during which the very existence of correlations must be learned, but Rieser also reported that alterations in the parameters of the correlations themselves remain informative throughout life. Another interesting finding Rieser discussed was that, when moving in a Ganzfeld, people do not simply rely on dead reckoning. They do better if they position imaginary objects and keep track of their movement with respect to these objects. Presumably this is a very human way of avoiding drift in the dead reckoning system. Puluwat Islanders teach it to novice navigators.

**Jeanne Sholl** has shown that, except in very restricted cases of regular and evenly-spaced arrays of objects, imagining rotations and also translations is not usually done within what she calls the object-to-object system, but instead involves positioning the imagined self and computing self-object vectors. These findings have implications for the development of perspective taking skills through middle childhood, as well as for direction giving, and the design of graphics and you-are-here maps.

### Spatial attention and motor control

In recent years it has become clear that there may be separate representations in the brain for “perceptual” information about space vs. information that is used to guide actions. For example, Milner and Goodale studied an agnosic patient known as DB who was unable to recognize objects or draw even simple shapes. However, DB appeared to have accurate information about an object’s shape when directing a motor action towards the object. For example, DB showed normal grasping movements of the fingers that were tuned to an object’s shape even though she was unable to produce even an approximate sketch of the same object. Milner and Goodale suggested that the “action system” (housed in dorsal areas of the brain) represents information about shape and spatial arrangement in an “egocentric” code that is short-lived and useful guiding reaching and other movements. In contrast, the ventral system preserves shape and location information that is allocentric and represents aspects of objects that are liely to remain invariant over relatively longer time spans. The papers in this session reinforced the importance of action in the representation of space.

**Linda Smith** discussed a novel interpretation of the well-known “A-not B-error” in terms of perseveration or priming of motor commands. This error occurs when an object is repeatedly hidden in a particular location and retrieved by the infant. When the object is now placed in a different location, in full view of the infant, he/she still searches at the old location. The traditional interpretation of this error supposes that young infants lack a mature concept of objects including their permanence or that they have faulty memories for spatial information. All of these explanations essentially place the origin of the error in the ventral system, which is responsible for “object knowledge”. A series of experiments, however, show that the critical component of the error hinges on engagement of the infant’s action system. For example, the same error is observed even when there is no hidden object. Merely repeatedly directing the infant’s attention to the same location over a series of trials produced the error even when on object was not hidden at that location. Smith emphasizes the role of repeated reaches to the same location in causing that response to become primed. When perceptual information about the exact target location is poor, as it often is in these experiments, the previously primed action may be sufficiently activated to produce a reaching error even when the infant presumably “knows” that the object is in a different location.

**Apostolos Georgopoulos** provides direct support for the involvement of the motor system in representing aspects of space that might have reasonably been attributed to non-motor areas. He recorded from single cells in the motor cortex while monkeys attempted to program an arm movement that involved the mental rotation of a location in space. One might suppose that this problem would be solved by applying a rotation transformation to a mental image and then sending the appropriate coordinates to the motor system for execution. Instead, Georgopoulos and colleagues observed activity in a population of motor cells that seemed to be carrying out the rotation transformation. In other words, the rotation was being carried out on a “motor” representation of the reaching movement to a location rather than its “visual” representation. In more recent work, they trained a monkey to respond on the basis of the serial position of a visual stimulus in a sequence. Monkeys were presented with a sequence of three to five yellow lights arranged around a circle. At the end of the sequence, one of the lights (the cue) was turned blue and the monkey had to move a cursor towards the light that had come on *after* the cue light. Success on this task requires the monkey assign a code to each object reflecting it’s ordinal location in the sequence. This information turned out to be present in the population of neurons that was responsible for producing the movement of the monkey’s arm to control the joystick. Some neurons in the motor cortex appeared to encode the ordinal position of the target. A given cell might always respond to the second light in the sequence regardless of its position. Other cells encoded only location while still others responded to an interaction of location and order. This seems to implicate motor areas of the brain in representing abstract information like temporal order. Neural net modeling showed that the population of recorded cells in the motor area contained sufficient information about location and order to successfully perform the task.

**Roberta Klatzky** reported a series of experiments showing that in navigation tasks accurate representation of egocentric position seems to depend on knowledge about self-motion. For example, imagining walking through a space (and making turns) results in systematic errors, which do not occur when the person walks a path blindfolded. Even “virtual reality” displays portraying the visual changes that occur when walking were a poor substitute for actual self-movement. Apparently, there are “automatic” processes in the brain, which detect changes in heading, and these processes are responsible for constantly updating one’s current position in space. Again, the message appears to be that in many tasks, there is an intimate connection between spatial representation and action.

### D. Neural bases of spatial competence

Maturation of the human brain, like behavioral development, sometimes occurs early in life and sometimes extends over longer periods of time and even into adolescence. Understanding the relation of the course of brain maturation to behavioral development in the spatial domain and to periods of possible high sensitivity to environmental input potentially provides information regarding how to time educational input and what kind of input to provide. Three presentations provided information on the organization of spatial skills at the neural level in adults, raising questions about development, modularity, and plasticity.

**Nancy Kanwisher** presented evidence from fMRI of the existence of a ‘parahippocampal place area’ (PPA) that is involved in a critical component of spatial memory and navigation. A bilateral area of parahippocampal cortex that straddles the collateral sulcus responds to passively viewed scenes, but only weakly to objects and not at all to faces. Its response to empty rooms is the same as to furnished rooms. Familiarity with the spaces does not affect reponsivity, nor does experiencing a sense of motion through the scenes. It is critical that the surfaces in the scene define a coherent space. It has also been shown that patients with damage to PPA have difficulty finding their way around novel environments. Overall, the working hypothesis is that PPA is used to encode perceptual information about the geometry of the local environment. Since disoriented human toddlers, as well as rats, have been shown to use geometric cues to reorient, does this mean that PPA is well-developed early on, and that there is a phylogenetically and developmentally primitive ‘geometric module’?

**Lynn Nadel** reported on the development of a virtual environment that can be used for investigation of place learning (i.e., use of distal cues to locate objects)in a laboratory setting. This is an important methodological tool that can be used with a variety of populations. Research using this tool has shown that place learning uses an integrated representation of relations among distal cues, rather than local views or snapshots, as had been proposed by other investigators. As expected based on this argument, performance is reduced if distal cues are transposed, but not if subsets are removed. Research has also shown that learning can occur even when participants are passively placed on a target ('teleported') and when they observe others navigate through the area.

**Brad Postle** has suggested that the caudate plays a part in spatial working memory (i.e., memory for object locations) but not in object memory. Early Parkinson's patients, who likely have differential loss of caudate function, show deficits in the task relative to normal controls. The conclusion is also supported by fMRI studies in humans, and lesion and electrical stimulation work in monkeys. However, a question is raised by the finding from monkey autoradiographic studies that the caudate is activated in both spatial and object delayed response tasks. It might be that human brains are organized differently or that fMRI is not sufficient to show this organization in humans.